

Field Dependent Coherence Length in the Superclean, High- κ Superconductor CeCoIn₅

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Using small-angle neutron scattering, we have studied the flux-line lattice (FLL) in superconducting CeCoIn₅. The FLL is found to undergo a first-order symmetry and reorientation transition at ~ 0.55 T at 50 mK. The FLL form factor in this material is found to be independent of the applied magnetic field, in striking contrast to the exponential decrease usually observed in superconductors. This result is consistent with a strongly field-dependent coherence length in CeCoIn₅, in agreement with recent theoretical predictions for superclean, high- κ superconductors.

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Since the discovery of heavy-fermion superconductivity in CeCoIn₅, a plethora of interesting phenomena have been observed in this material. Among these are one of the highest critical temperature ($T_c = 2.3$ K) in any heavy-fermion superconductor [1], d -wave pairing symmetry [2, 3], field- and pressure-induced quantum-critical points and non-Fermi liquid behavior [4, 5, 6, 7, 8], strong indications of the first realization of a non-uniform Fulde-Ferrell-Larkin-Ovchinnikov state [9, 10, 11, 12, 13, 14], and suggestions of multi-band or multi-order parameter superconductivity [15, 16].

In addition, CeCoIn₅ is also found to represent an extreme case of a clean, high- κ superconductor. The elastic electronic mean free path in this material ranges from $l = 840$ Å at T_c [17], increasing exponentially as the temperature is decreased and reaching values of 4 to 5 μ m at 400 mK [18, 19]. Literature values for the penetration depth varies from 190 nm [18] to 280 nm [20]. Estimates of the orbital critical field based on $dH_{c2}/dT|_{T_c}$ range from $H_{orb}^{lc}(0) = 13.2$ T [17] to 15.0 T [21], yielding an in-plane coherence length of $\xi_{orb} = 47 - 50$ Å, and hence $\kappa = 40 - 60$ and $l/\xi \sim 10^3$ or larger at temperatures below a few hundred milliKelvin.

In many superconductors, detailed information about the nature of the superconducting state has been obtained from small-angle neutron scattering (SANS) studies of the flux-line lattice (FLL). Examples of this are FLL symmetry transitions driven by non-local electrodynamics [22] or a superconducting gap anisotropy [23, 24], and subtle changes in the fundamental length scales obtained from the FLL neutron reflectivity [25, 26]. In this Letter we report on SANS studies of the FLL in CeCoIn₅. In striking contrast to the exponential dependence usually observed in superconductors, the FLL form factor in this material is found to be independent of the applied magnetic field. This result indicates a coherence

length which decreases with increasing field, in qualitative agreement with recent theoretical predictions for clean, high- κ superconductors [27].

The SANS experiments were carried out at the D22 and D11 instruments at the Institut Laue-Langevin. The CeCoIn₅ single crystals used in the experiment were grown from excess indium flux, and had a $T_c = 2.3$ K and a $H_{c2}(0) = 5.0$ T for fields applied parallel to the c axis [1]. The sample was composed of three individually aligned single crystals with thicknesses 0.13 - 0.22 mm mounted side by side. The total mass of the sample was 86 mg. The use of rather thin crystals was necessary, due to the strong neutron absorption by indium. Incident neutrons with a wavelength of $\lambda_n = 4.5$ Å (D11) and 7 Å (D22) and a wavelength spread of $\Delta\lambda_n/\lambda_n = 10\%$ were used, and the FLL diffraction pattern was collected by a position sensitive detector. For all measurements, the sample was field-cooled to a base temperature of 40 - 50 mK in a dilution refrigerator insert, placed in a superconducting cryomagnet. Horizontal magnetic fields in the range 0.4 - 2.0 T were applied parallel to the crystalline c axis and the incoming neutrons. Background subtraction was performed using measurements following zero-field cooling.

Fig. 1 shows FLL diffraction patterns obtained at three different applied fields. Each image is a sum of the scattering from the FLL, as the sample is rotated and tilted in order to satisfy the Bragg condition for the different reflections. At fields below 0.55 T, 12 (2×6) reflections are observed as shown in Fig. 1(a), corresponding to two nearly hexagonal domains with Bragg peaks aligned along $\langle 100 \rangle$ -directions. As the field is increased above ~ 0.55 T the FLL undergoes a first order transition to a rhombic symmetry as shown in Figs. 1(b) and (c). Again two rhombic FLL domain orientations are observed, indicated by the 8 (2×4) Bragg peaks. As evident from

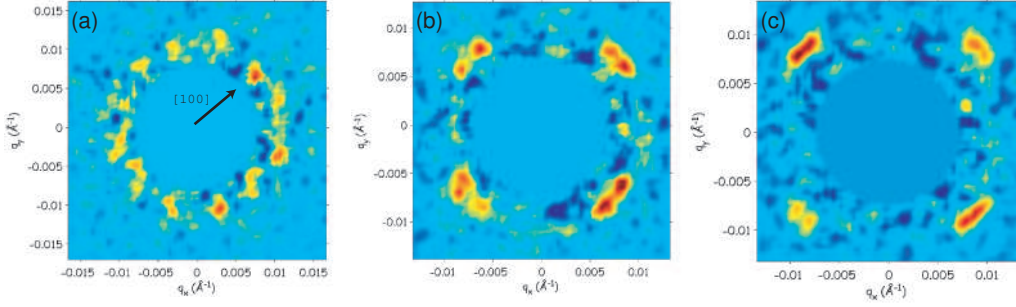


FIG. 1: (Color) FLL diffraction patterns for CeCoIn₅ with applied fields 0.5 T (a), 0.55 T (b) and 0.75 T (c), after subtraction of background measurement. The data is smoothed and the center of the image is masked off. The crystalline a axis is vertical.

the decreasing peak splitting in the rhombic phase, the FLL gradually evolves towards a square symmetry as the field is increased. These results are in agreement with our earlier studies [28].

The evolution of the symmetry transition, quantified by the FLL opening angle β , is summarized in Fig. 2. Though it was not possible to reliably fit and extract a FLL split angle above 0.85 T, high-resolution measurements up to 1.0 T still showed a weak rhombic distortion. A linear extrapolation of the opening angle to $\beta = 90^\circ$, yields a transition field $H_2 = 1.1$ T above which a perfectly square FLL is realized. Besides the opening angle, we also used scattering vectors belonging to the same domain to obtain the internal field by the relation $\mathbf{q}_1 \times \mathbf{q}_2 = (2\pi)^2 B / \phi_0$, where $\phi_0 = 20.7 \times 10^4 \text{ T}\text{\AA}^2$ is the flux quantum. From this we obtain $dB/d(\mu_0 H) = 0.992 \pm 0.012$, which leads us to set $B = \mu_0 H$ for the remainder of this work.

A square FLL can either be stabilized by a gap anisotropy as observed e.g. in YBCO [24], or by non-local electrodynamics coupled with a Fermi surface anisotropy as seen in the borocarbide superconductors [22, 29]. In

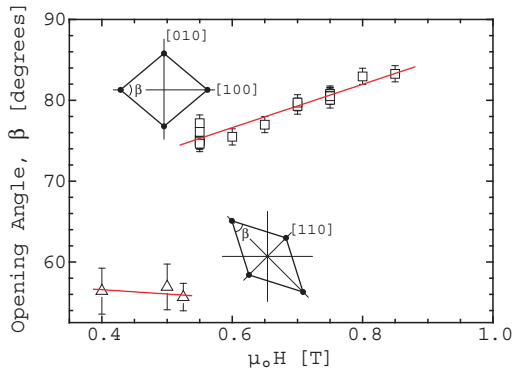


FIG. 2: Field dependence of the FLL opening angle, β . The insets show the real space orientation of the FLL unit cell in the low and high field configurations.

the case of CeCoIn₅ the orientation of the gap nodes have been subject to controversy [2, 3, 16], although recent theoretical work aimed at resolving this issue concluded that the pairing symmetry in this material is $d_{x^2-y^2}$ [30]. As we have previously reported, such an orientation of the gap nodes is consistent with the high-field square FLL being stabilized by d -wave pairing [28]. On the other hand, an extrapolation to $H = 0$ of the the high-field opening angle in Fig. 2 yields $\beta \approx 60^\circ$, as expected if the FLL symmetry is determined by non-local effects [29].

We now turn to measurements of the FLL form factor, which are the main results of this Letter. Fig 3(a) shows the FLL reflectivity obtained from the integrated intensity of the Bragg peaks, as the sample is rotated through the diffraction condition. The reflectivity is given by

$$R = \frac{2\pi\gamma^2\lambda_n^2 t}{16\phi_0^2 q} |F(q)|^2, \quad (1)$$

where $\gamma = 1.91$ is the neutron gyromagnetic ratio, λ_n is the neutron wavelength, t is the sample thickness, and q is the scattering vector [31]. The form factor, $F(q)$, is the Fourier transform of the magnetic field profile around a vortex, and depends on both the penetration depth and the coherence length. Fig. 3(b) shows the FLL form factor determined from the reflectivity. Here we have used the measured opening angle, $\beta(H)$, in Fig. 2 to determine the magnitude of the scattering vector, and hence compensate for effects due to the FLL symmetry transition. In the high-field rhombic FLL phase $q_{\text{sq}} = q_0 / \sqrt{\sin \beta}$ where $q_0 = 2\pi\sqrt{B/\phi_0}$. In the low-field distorted hexagonal phase, the 4 Bragg peaks aligned along the $\langle 100 \rangle$ -direction have $q_{\text{hex1}} = q_0 \sqrt{2(1 - \cos \beta)} / \sin \beta$, while for the remaining 8 peaks $q_{\text{hex2}} = q_0 / \sqrt{\sin \beta}$.

The field-independent form factor observed for CeCoIn₅ is in striking contrast to the exponential decrease observed in other superconductors. However, it is important to note that if the form factor was truly independent of q , this would imply an unphysical situation with a diverging magnetic field at the vortex center and a coherence length equal to zero. To reconcile this appar-

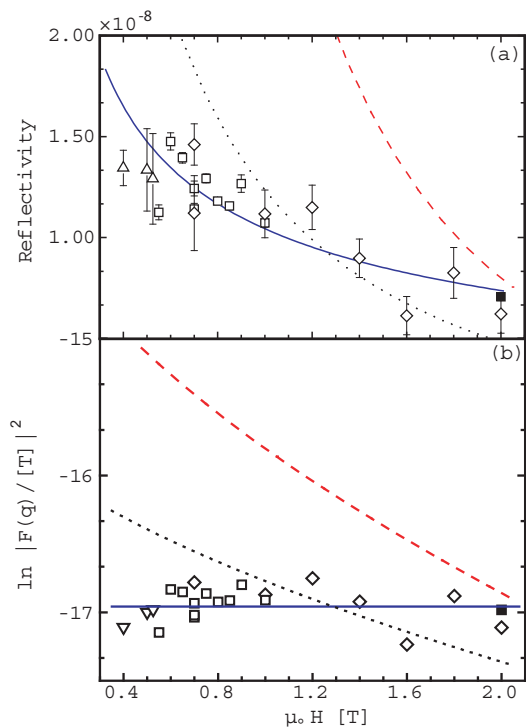


FIG. 3: Field dependence of the reflectivity (a) and form factor (b) for the (1,0) FLL Bragg reflections. Triangles correspond to a hexagonal FLL and the squares and diamonds to a rhombic FLL. The solid square is from previous work [28]. The dashed and dotted lines are calculated using Eqs. (1) and (2) with the following values for the coherence length and the penetration depth: $\xi = 81$ Å, $\lambda = 2350$ Å (dashed line); $\xi = 50$ Å, $\lambda = 3750$ Å (dotted line). The solid line corresponds to a constant form factor, $F = 2.08 \times 10^{-4}$ T.

ent paradox, it is necessary to assume a field dependence of either the superconducting penetration depth, the coherence length or both.

Several models exist for the magnetic field profile around the vortices. In the following we have based the analysis on the form factor obtained by Clem [32]:

$$F(q) = B \frac{g K_1(g)}{1 + \lambda^2 q^2}, \quad g = \sqrt{2}\xi (q^2 + \lambda^{-2})^{1/2}, \quad (2)$$

valid for $\kappa \gg 1$. It is worth to point out that while this form factor was obtained for an isotropic superconductor, numerical simulations found no significant difference between superconductors with s - or d -wave pairing [33].

The dashed lines in Figs. 3(a) and (b) show the reflectivity and form factor calculated from Eqs. (1) and (2) using an average literature value for the penetration depth $\lambda = 2350$ Å and $\xi_{c2} = \sqrt{\frac{\phi_0}{2\pi H_{c2}}} = 81$ Å. As already discussed, these calculated values are not consistent with the experimental data. However, a more appropriate value for the coherence length is obtained from the orbital critical field, $\xi_{orb} = \sqrt{\frac{\phi_0}{2\pi H_{orb}}} \approx 50$ Å [17, 21].

This does correspond to a smaller slope of $|F(q)|^2$, but also increases the discrepancy between the measured and calculated values of $|F(q)|^2$ since, for a given ξ and q (or H), the magnitude of the form factor is determined by λ^2 . Using the penetration depth as a fitting parameter, one obtains the dotted lines in Fig. 3 for $\lambda = 3750$ Å. Although this provides a better agreement with the data, such a large value of λ is not consistent with reports in the literature [18, 20]. In contrast, a perfect fit to the data is obtained with a constant value of the form factor, $F = 2.08 \times 10^{-4}$ T, and correspondingly a reflectivity $\propto 1/q$, as shown by the solid lines in Fig. 3.

It is important to note that no significant disordering of the FLL is observed. Except for systematic differences between the two beamlines, the FLL rocking curve widths remain essentially constant throughout the measured field range. On D22 we find rocking curve widths going from $0.14^\circ \pm 0.02^\circ$ FWHM at 0.55 T to $0.16^\circ \pm 0.01^\circ$ FWHM at 1 T, comparable to the experimental resolution ($\sim 0.08^\circ$ FWHM). Below the reorientation transition a slightly higher value of $0.20^\circ \pm 0.04^\circ$ FWHM is observed. On D11 FLL rocking curve widths decrease from $0.26^\circ \pm 0.03^\circ$ FWHM at 0.7 T to $0.19^\circ \pm 0.01^\circ$ FWHM at 2 T. Such narrow rocking curve widths indicate a very well ordered FLL with a longitudinal correlation length in the micron range, consistent with weak pinning due to the high cleanliness of CeCoIn₅. Furthermore, FLL disorder above a certain threshold has been shown to lead to decrease in the scattered intensity, exceeding the usual exponential field dependence of the form factor [34]. We can therefore exclude FLL disordering as the cause for the field-independence of the form factor in CeCoIn₅.

A constant form factor could in principle be due to a decrease of the penetration depth with increasing field, caused either by an increasing superfluid density or a non-uniform spin magnetization contributing to the magnetic flux carried by each vortex. We do not consider the first possibility realistic. Furthermore, while CeCoIn₅ is indeed paramagnetic [21], spin polarization effects will lead to an enhancement of the form factor in contrast to the strong suppression observed in this material [35, 36]. We therefore conclude that while paramagnetic effects may contribute, they are not the dominating mechanism behind the field-independent form factor. In the following we therefore restrict our analysis to consider only a field-dependent coherence length.

In Fig. 4, we show the coherence length obtained by varying ξ to achieve the measured form factor at each field. The coherence length is found to follow a $1/\sqrt{H}$ behavior. While different models for $F(q)$ will provide slightly different values for the coherence length, the qualitative behavior will remain unchanged. Fig. 4 also shows the extracted coherence length as a function of intervortex spacing, a . Within the experimental error shown by the scatter in the data, the coherence length is found to increase linearly with the intervortex spacing

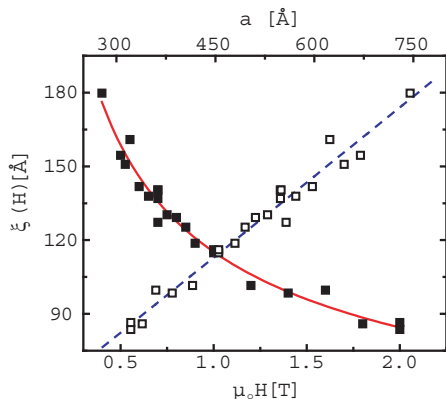


FIG. 4: Field dependence of the coherence length, $\xi(H)$ plotted versus applied field (solid symbols), and vortex separation (open symbols). The solid and dashed lines are fits to the data described in the text.

while at all times satisfying $\xi < a$. Extrapolating to a vortex separation of 125 Å (corresponding to an orbital critical field $H_{\text{orb}} = 13.2$ T) yields $\xi = 43.0 \pm 4.6$ Å, in reasonable agreement with $\xi_{\text{orb}} = 50$ Å.

We believe that our data provide the first example of a strongly field-dependent coherence length in a superclean, high- κ superconductor as recently theoretically predicted by Kogan and Zhelezina [27]. In their model, the coherence length is predicted to be proportional to $1/\sqrt{H}$ and correspondingly depends linearly on the vortex separation. Experimentally we find $d\xi/da = (0.55 \pm 0.02)/\sqrt{2\pi}$, which is roughly twice the theoretically predicted slope [27]. However, the theoretical prediction was based on assumptions of weak-coupling s -wave superconductivity and a simple Fermi surface topology (sphere or cylinder), which are not valid for CeCoIn₅. Based on this we argue that the agreement between theory and experiment is remarkable, supporting the universal nature of the effect. At low fields the model predicts the coherence length to saturate. Based on our experimental results this cut-off in CeCoIn₅ occur below the lowest measured field of 0.4 T. We believe that the field-dependent coherence length is so prominently observed in CeCoIn₅ due to the combination of a large κ and the very high cleanliness of this material.

Additional evidence for the unusual magnetic-field response of CeCoIn₅ has been observed in the quasiparticle mean free path, as extracted from measurements of the Hall angle [37]. Specifically, the mean free path is found to decrease as the applied field increases, being roughly equal to the vortex separation for the range of fields covered by our SANS measurements. This leads us to speculate that a connection exists between ξ and l beyond the simple Pippard model.

Finally, we want to note that while previously reports of a field dependent vortex core size have been made by Sonier *et al.* [38, 39], these were attributed to a vortex-

squeezing effect. However, since the variation of the vortex core size in these cases was significantly smaller than for CeCoIn₅, we do not believe that such effects can explain the data reported here.

In summary, we have presented SANS measurements of the FLL in CeCoIn₅. These measurements indicate a strong reduction of the superconducting coherence length with increasing field, in qualitative agreement with recent theoretical predictions for superclean, high- κ superconductors.

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